Surface Wave Processes on the Continental Shelf and Beach

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LONG-TERM GOALS

There is a growing need for surface wave information on the continental shelf and beach to estimate sea state, and to provide input for models of currents, sediment transport, radar backscatter and aerosol generation. While surface wave spectra in the open ocean evolve slowly over distances of O(100-1000 km), wave properties on the continental shelf and beach are highly variable (typical length scales of 0.1-10 km) owing to a variety of topographic effects (e.g., shoaling, refraction, scattering) and strongly enhanced nonlinear interactions and dissipation. The long-term goal of this research is to develop a better understanding of the physical processes that affect the generation, propagation and dissipation of surface waves in shallow coastal waters, and improve the accuracy of models that predict the transformation of wave properties across the shelf and beach.

OBJECTIVES

- predict accurately the nonlinear shoaling transformation of ocean surface waves on beaches including the excitation of infragravity motions

- evaluate models for wave dissipation by bottom friction

- determine the scattering effects of resonant wave-wave and wave-bottom interactions on the evolution of wind sea and swell spectra on the continental shelf

- improve the representation of source terms in operational wave prediction models

- determine the importance of wave reflection and trapping by steep submarine topography

APPROACH

A combination of theory, analytical and numerical models, and field experiments is used to investigate the physical processes that affect surface wave properties on the continental shelf and beach. The transformation of wave spectra across the continental shelf is predicted with models based on a spectral energy balance that include the effects of refraction, scattering by resonant interactions (e.g., wave-bottom triads and wave-wave quartets), and bottom friction. A different approach is used near the shore where near-resonant wave-wave triad interactions cause a rapid transfer of energy to harmonic components and lower-frequency infragravity waves. A new model is developed, based on a

stochastic closure of Boussinesq theory, that predicts the nonlinear shoaling transformation of a random, directional wave field across a beach. Extensive field data are used to verify predictions of topographic and nonlinear effects, and to estimate the energy losses owing to bottom friction and wave breaking. The data sets include measurements from arrays of pressure sensors, current meters, and directional buoys deployed in a series of experiments (DUCK94, SandyDuck, SHOWEX) on a wide shelf with a relatively straight beach along the North Carolina coast. A new experiment (NCEX) is in progress on the southern California coast to study wave transformation over a steep, irregular shelf. Analysis techniques applied to the measurements include various inverse methods to extract directional and wavenumber properties from array cross-spectra, bispectral and trispectral analysis to detect nonlinear coupling, as well as standard statistical methods to determine empirical relationships between observed variables.
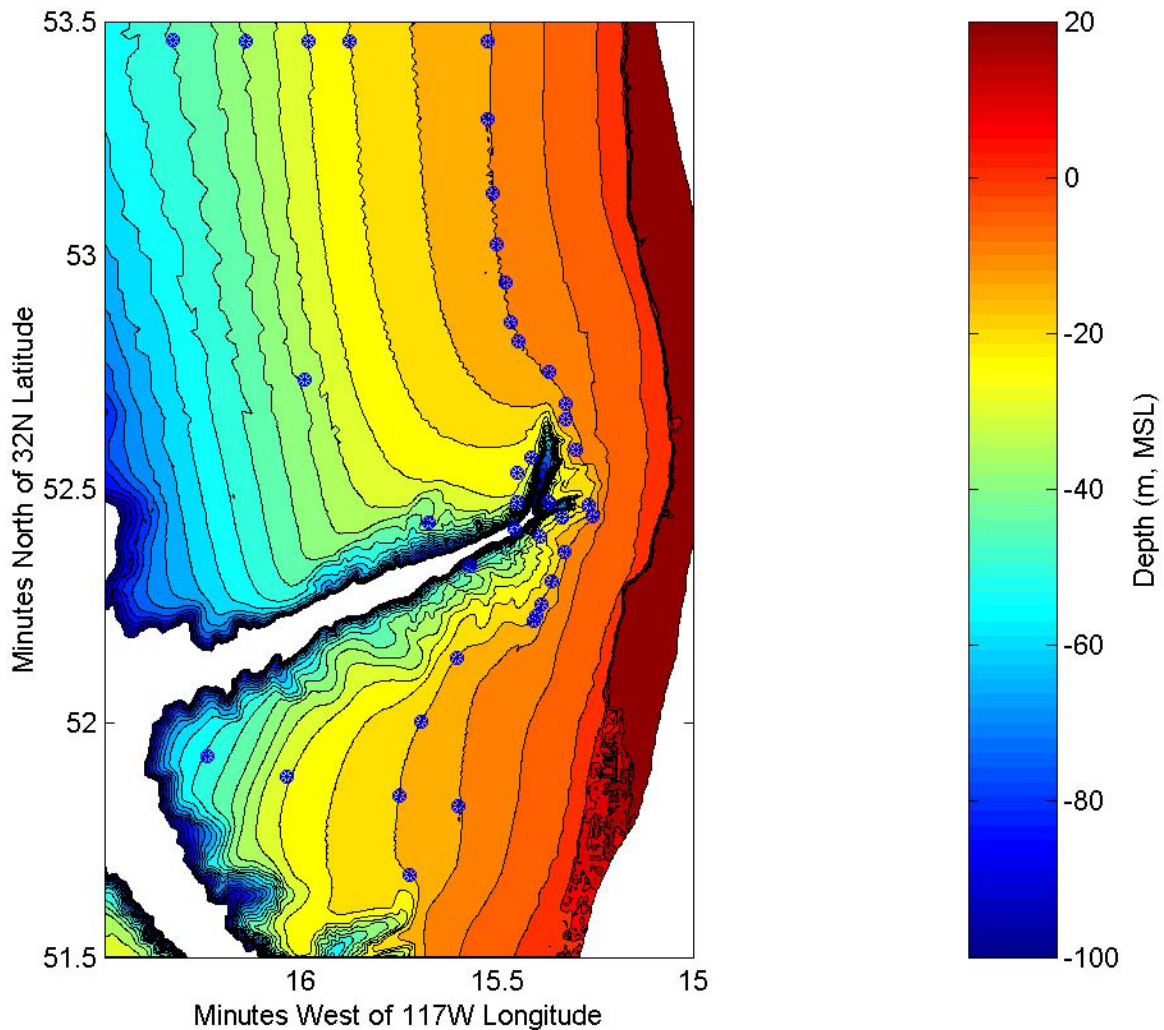

Figure 1. Plan view of instruments deployed during September 2003 (in collaboration with W. C. O'Reilly and S. J. Lentz) near La Jolla, California, as part of the NSF/ONR Nearshore Canyon Experiment.

WORK COMPLETED

During September 2003 a large array of wave- and current measuring instruments was deployed offshore of La Jolla, California, as part of the Nearshore Canyon Experiment (NCEX), funded jointly by ONR and NSF. In collaboration with Drs. W. C. O'Reilly (SIO) and S. J. Lentz (WHOI), 7 surface-following wave buoys, 17 bottom pressure recorders, 12 pressure-velocity sensors and 7 current profilers were deployed in depths ranging from 10-50 m (Figure 1). This array will be used in conjunction with an extensive surf zone array deployed by Drs. S. Elgar (WHOI) and R. T. Guza (SIO) to investigate the effects of a submarine canyon on the shoaling transformation of waves and the associated nearshore circulation. Preliminary analysis of pilot data collected during the fall of 2002 confirms the pronounced refraction of swell over the complex two-dimensional bathymetry and associated extreme nearshore wave height variations that were first reported in a classic study by Munk and Traylor (1947). Graduate student Rudy Magne (University of Toulon, France) will investigate the scattering effects of the steep submarine canyon walls on the incident swell using a new theory developed recently by Athanassoulis and Belibassakis (1999). Graduate student Jim Thomson (MIT/WHOI Joint Program) will focus on the generation and topographic trapping of lower frequency (infragravity) waves.

RESULTS

A Boussinesq model for the nonlinear transformation of ocean surface waves in shallow water was tested with extensive field and laboratory observations. Outside the surf zone the model accurately predicts the observed spectral evolution, including energy transfers to harmonic components traveling in the direction of the dominant waves, and the cross-interactions of waves traveling in different directions that transfer energy to components with the vector sum wavenumber (Herbers et al., 2003). Effects of surf zone wave breaking were incorporated with a heuristic frequency-dependent dissipation term in the spectral energy balance equation and a relaxation to Gaussian statistics. The associated coefficients were calibrated with observations that span a wide range of surf zone conditions. The robustness of the surf zone parameterization is illustrated in Figure 2 with model-data comparisons during the peak of a severe nor'easter storm on 15 October, 1994, when the majority of the instruments were within the surf zone. The significant wave height decreased from about 3.4 m in 8 m depth to 0.8 m in 1 m depth (Figure 7b). The model predicts accurately the observed evolution of the frequency spectrum from an initially narrow spectrum (0.09 Hz peak frequency) with a pronounced harmonic peak (0.18 Hz) to an almost uniform spectrum in the inner surf zone (Figure 7f-i). Predictions of sea surface skewness and asymmetry, bulk parameters often used to characterize average wave shapes, also agree fairly well with observations (Figure 7c,d). In particular, the model reproduces the observed evolution of asymmetry (i.e. the steepness of wave fronts), increasing from small values offshore to a maximum over the sand bar, decreasing to small values in the downslope region inshore of the bar crest, and increasing again on the beach face. The observed directional spectra inside the surf zone are broader than the predicted spectra (Figure 2e), suggesting that neglected scattering effects associated with the random onset of wave breaking or with higher-order nonlinearity may be important.
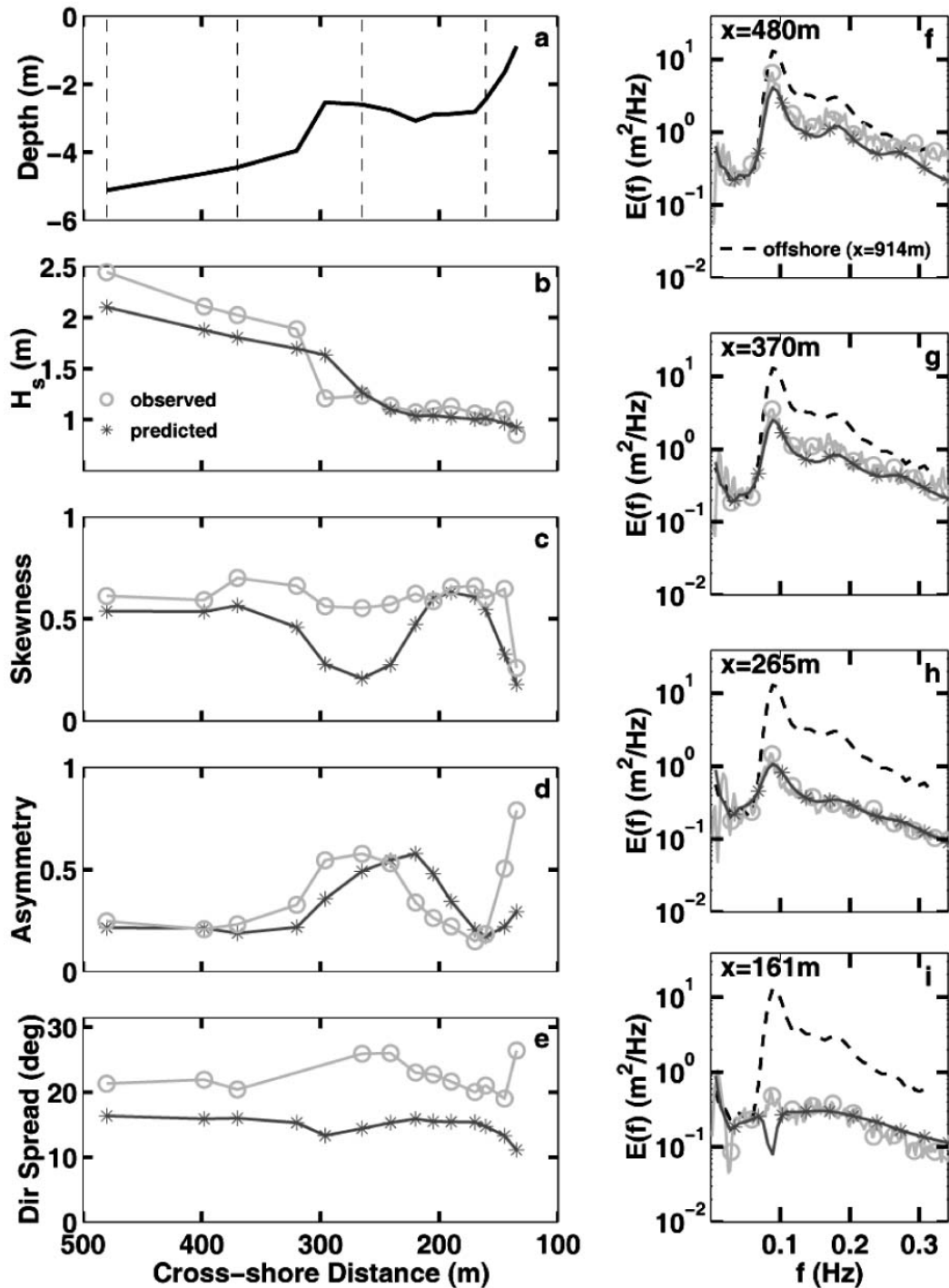
Figure 2. Comparison of observed (circles on light curves) with predicted (asterisks on dark curves) wave transformation across the surf zone on 15 October, 1994. Left panels: (a) water depth, (b) significant wave height, (c) skewness, (d) asymmetry, and (e) directional spread versus cross-shore distance. The model was initialized in 8 m depth (cross-shore location 914 m) where the significant wave height was 3.4 m. Right panels show frequency spectra at four locations (indicated with dashed lines in (a)): (f) outer surf zone, (g) seaward of the sand bar, (h) on the bar crest, and (i) inshore of the bar crest. For reference the initial spectrum observed in 8 m depth is indicated in each panel with a dashed curve. (from Herbers et al., 2003)

IMPACT/APPLICATIONS

Analysis of swell decay during SHOWEX (Ardhuin et al., 2002, 2003a,b) shows that as much as 90% of the incident wave energy flux is dissipated on the shelf and the dissipation rates appear consistent with existing bed roughness models. This dramatic sheltering of a coastline with a wide, sandy shelf has important implications for nearshore hydrodynamics and sediment transport.

RELATED PROJECTS

Results of this research are adapted and implemented in a comprehensive nearshore community model that is being developed under sponsorship of the National Oceanographic Partnership Program (NOPP) (Lead-PI: J. T. Kirby).

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